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FEASIBILITY STUDY OF ZERO G DEVICES

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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ABSTRACT: A thorough investigation was conducted into the various possible ways that a practical "zero g" sensing device might be achieved. Many physical phenomena, dependent on gravity, were considered as a possible avenue for a solution to the problem. Devices employing these phenomena were developed in sketch form with the emphasis on meeting the following requirements: (1) the device must be purely mechanical except for the energy to start the timer, (2) it must be omnidirectional (e.g., function when the g vector is at any angle with respect to the axis of the device), (3) it must fail safe, and (4) it must sense weightlessness either continuously or intermittently for a prescribed time interval. A comparison of the devices was made as to how well each met the above requirements; the most promising were selected for further development with the immediate aim being a functional model.

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Most ballistic missiles utilize two environments in their safety and arming systems: (1) acceleration at launch and (2) deceleration upon re-entry. However, there are some missiles that are detonated before re-entry and for these there is a need for sensing another phenomenon unique to the missile in flight. There are numerous phenomena which might be used but this report is restricted to the investigation of one of these, namely "zero g" or weightlessness.

Many phenomena were investigated as to how they might be employed in achieving a practical device. The results of this brain-storming session were twelve designs, of which three seemed to offer the most promising possibilities. These are discussed in some detail in the ensuing report.

This is the first report on the subject of "zero g" devices. The work described herein was performed under Tasks No. RREN 04004/212 1/F008/21 002. and RREN 04322/212/1/F008-21/02.

This report is to be used for information purposes only and is not intended to be used as a basis for direct action.

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By direction

CONTENTS

ILLUSTRATIONS

FEASIBILITY STUDY OF ZERO G DEVICES

INTRODUCTION

1. At present, almost without exception, all safety and arming devices in ballistic missiles have as their basis some type of an accelerometer, which utilizes the principle of "set-back" or the reaction to the force causing acceleration. However, in considering the intermediate range ballistic missile, we encounter another phenomenon which is peculiar only to a given missile in flight, namely, that of weightlessness. This condition exists when the missile velocity and radius of curvature are such that the centrifugal force equals the gravitational force. Stated in different terms, this condition exists when the re-entry body is in the vacuum portion of its ballistic trajectory and freely falling. Other phenomena such as radiation cooling differences, zero pressure, cosmic radiation differences, etc., also exist in this environment but in this report we are only concerned with "zero g".

2. Even though the missile may go through the so-called period of "weightlessness" or zero g, it none-the-less will experience a slight g loading (of the order of .lg) due to its own spin, tumbling, etc., in space.

3. Due to the energy imparted to it at separation, the re-entry body may take an infinite number of positions in space. This random orientation dictates that our zero g device must function equally well in all planes.

4. Since it would be possible to simulate weightlessness for as long as 30 seconds during an aircraft programmed flight on a parabolic trajectory, we must design the device to sense .lg for a period in excess of this value. If the device must sense .lg for, say, 60 seconds, then the only environment where we would satisfy this requirement would be when the missile is in unimpeded ballistic flight path.

5. It is also desired that the device have a positive lock; that is, once it has sensed a g level greater than .lg and locks, it should not function again if the g level returns to .lg or less.

6. An extensive list of phenomena which vary with gravity was made. An investigation into the possible application of these phenomena in a zero g device resulted in practical

devices in some cases and in other cases no practical solution was found at this time. The following is a list of the phenomena investigated:

a. Position of a free or lightly restrained mass with no initial velocity.

(1) location of a free mass: $s = \frac{1}{2}gt^2$

(2) trajectory of a projectile: $F_y = mg$; $s_y = \frac{1}{2}gt^2$

(3) location of a mass experiencing a buoyant force:

F_o = net force out

W_a = weight of solid object in air

V_o = volume of solid object immersed

ρ_o = density of solid object

ρ_ℓ = density of liquid

$$F_o = W_a - F_b$$

$$F_o = V_o \ (\rho_o - \rho_\ell)g$$

$$s = \frac{V_o}{2} \ (\rho_o - \rho_\ell)gt^2$$

b. Velocity of a free or lightly restrained mass with no initial velocity

(1) All the examples of (a.) with $s = \frac{1}{2}gt^2$ changed to $v = gt$

c. Acceleration of a free or lightly restrained mass

(1) All the examples of (a.) with $s = \frac{1}{2}gt^2$ changed to $a = g$

d. Force required to support a mass

(1) Weight of a mass in air: $w = mg$

(2) Weight of a mass immersed in a liquid: $F_o = W_a - F_b$

(3) Pressure gradient within a hydraulic system:

$$P = F/_A = \rho g h$$

e. Impact of a free fall: $Ft = mv$; $v = \sqrt{2gh}$

f. Precession of a mass loaded gyro: $\tau = I\omega\Omega$; $\tau = mg\ell$

g. Frequency of a simple pendulum: $f = \frac{1}{2\pi}\sqrt{\frac{g}{\ell}}$

h. Position of a conical pendulum: $\cos\theta = \frac{g}{\omega^2 \ell}$

i. Torque of all systems under (d.): $\tau = mgr$

j. Convection currents in fluids: (vary with density differences)

k. Frictional force due to normal load: $f = \mu N = \mu mg$

l. Shape or height of a liquid due to surface tension: (as gravity decreases, force due to surface tension becomes predominant over inertial force).

It is interesting to note at this point that in sensing a phenomenon at .1g and 1g, we would get a ratio of 10:1 if the phenomenon varies linearly with g; however, for those phenomena in which g appears under a radical, we get a variation of only $\sqrt{10}$ or 3.16. This is, of course, the maximum variation that can possibly be attained in the ideal case. In reality, due to components of force, frictional losses, tolerances, etc., we get much less variation with which to work.

RESULTS

7. One device that appears to meet all of the requirements is shown schematically in Figure 1. This device is an application of paragraph 6.d.(1) in that a force due to the weight of the ball acts normal to the wedge surface and exerts a torque on the pivoted arm; this torque is opposed by a torque created by a compression spring force acting at a distance d from the pivot. When the ball is acted upon by .1g, the two torques are equal and the system is in equilibrium; however, on increasing g, the torque exerted by the ball increases while the spring torque remains constant, merely because it depends only on the separation between the pivoted arms. In this instance, the ball causes the arms to rotate outward, locking them in the cam recesses, and stops the clock. No matter what orientation we give the device, there will always be a force on the arm due to the ball either by a wedging action or a direct component of the weight. Either one or both of the arms moving outward is sufficient to lock the device.

Once the arms are locked in the recesses, there is no possibility of the device functioning again. By proper selection of the wedge angle, the net force on the arm when gravity acts along the y axis can be made to equal the net force when gravity acts along the x axis.

8. Another device that appears to meet all the requirements is an application of paragraph 6.i. and is shown in Figure 2. A constant speed clock with a given torque drives three eccentric weights about the x, y and z axes, respectively. The weights are driven by means of a drum attached to the clock shaft; this drum has two circular racks (one around the side wall and one in the top) which engage pinions to which the weights, through a shaft, are attached. The shafts are rotating in ball bearings to minimize the resisting torque due to friction. If we denote the weight as "W" and the distance to its center of gravity as "c", then the maximum resisting torque that each weight can present during 360° of shaft rotation is Wc. This will occur when the line connecting the center of gravity to the center of rotation is normal to the gravity vector and the weight is on the upswing. When this line is parallel to the gravity vector, the required torque for rotation will be zero. A plot of torque vs degrees rotation will show the function to be sinusoidal. For the device to be omnidirectional, it must have a net system torque (summation of the combined individual torques at a given time) regardless of the particular orientation. The clock must overcome this total system torque in order to function. A preliminary investigation reveals that the total system torque will have a minimum value of 2.0 Wc when the gravity vector is parallel to a principal axis and a maximum value of 2.414 Wc when the gravity vector is normal to one axis and makes a 45° angle with the other two axes. Thus, if we select a clock with a torque rating equal to that of the system at .1g, then any increase in g would result in a load that would be too great for the clock to overcome.

9. Another device that shows some promise is one that utilizes the principle of the position of a body in free fall as given in paragraph 6.a.(1) and is shown in Figure 3. This device rapidly releases two balls which are immediately caught again if the g level is .1 or less. If the g level is greater than .1, either one or both of the balls escapes, thus locking the mechanism. Looking at Figure 3, we see that the ball is initially held between two concave holders which are under the combined forces of a tension and compression spring. The holders are restrained from moving outward as long as pin "A" is in contact with the inner surface of the cam. When pin "A" finds a slot or opening on this inner surface, the holders are triggered and move out and back under the

tandem action of the two springs. Since some energy is lost in the total excursion, it is necessary to cam the holders back to their initial positions. The relative displacement between the inner and outer portion of the holder allows us to accomplish this while holding the ball. This same displacement also locks the cam and hence the clock in the event the ball is lost. When the ball is missing, pin "B" advances toward pin "A" and moves into the slot in the cam, locking it. The total open time for the holders is of the order of 100 milliseconds while the hold time might be from three to five seconds. The concave surface on the holders insures that the ball will be squeezed back to its starting position each time. This avoids the possibility of the ball escaping by a summation of small incremental drops.

Discussion

10. The device of section 7 can be analyzed on the basis of a torque due to the weight of the ball acting against a torque due to a compression spring. Since the spring torque is determined by the separation of the arms (which determines the amount of spring compression) and a fixed moment arm, it is independent of the orientation of the device; however, the ball torque depends on the normal force exerted by the ball on the wedge (which varies with arm separation) and on the moment arm (point of tangency of ball on wedge) which varies with the orientation. Therefore, there is a range of variation of ball torque for a given g level and this variation is due to the particular position in space that the device assumes. If the device is designed to be in equilibrium (ball torque equals spring torque) at .1g when the orientation is such as to produce the maximum ball torque effect, then in any other position, it will take an increased g level to cause locking. A preliminary investigation indicates that this increased g level will reach a maximum at approximately .3g. Therefore, we can state that the device will always function at .1g or less, it will always lock at .3g or greater and between these two extremes, it can go either way, depending on its orientation.

11. The device of section 8, which requires that the torque inherent in the clock spring overcome the resistance due to the three unbalanced weights, seems to best meet the requirement of being omnidirectional of the devices presented in this report. Ideally, with a ratio of minimum resistance to maximum resistance of 83%, the device would always function below .1g, always lock above .12g and have a questionable result at values between these two extremes. One effect, however, that we must prevent in this device is the speeding up of the weight as it goes from a position of maximum

potential to minimum potential energy; that is we must have a constant or nearly constant speed clock. The shafts connecting the pinion and weight would be mounted in ball bearings to minimize the differential between starting resistance (static friction) and running resistance (kinetic friction).

12. The device of section 9, which senses the distance a ball falls in a given time, has an inherent disadvantage in the basic equation. Since $S = \frac{1}{2}gt^2$ or the distance is proportional to the time squared, a slight variation in time means a squared variation in distance. The holders of the ball are opened mechanically by a cam which releases a plunger under spring force; the time difference for one complete cycle of opening and closing the holders depends on such things as spring tolerances, simultaneous movement of holders, total travel of plunger, etc. To keep the device at a practical size, we are speaking of a drop time differential (total time necessary for the ball to escape the holders) of the order of 100 milliseconds. All of these factors add up to a highly precise device with very close tolerances. A possible relaxation of this precision might be achieved if the ball could be dropped in a buoyant medium, thus giving a greater time differential for a given free fall distance. A preliminary investigation of this device seems to indicate that it presents more problems in attaining a workable design than the other two. The maximum drop distance for the ball to clear the holders would occur at a 45° angle with one of the principal axes and would be 41% greater than the distance along the principal axis; there is also the possibility of the falling sphere striking the concave surface of the holder as it opens on this same 45° angle which would result in an increased path length and hence incorrect time.

CONCLUSION

13. The device of section 7 (ball acting against inclined surface of two pivoted plates) appears to have outstanding possibilities and will be developed further with the initial goal being a practical working model.

14. A second device will also be developed concurrently with the above mentioned one and will be selected from the other two presented in this report.

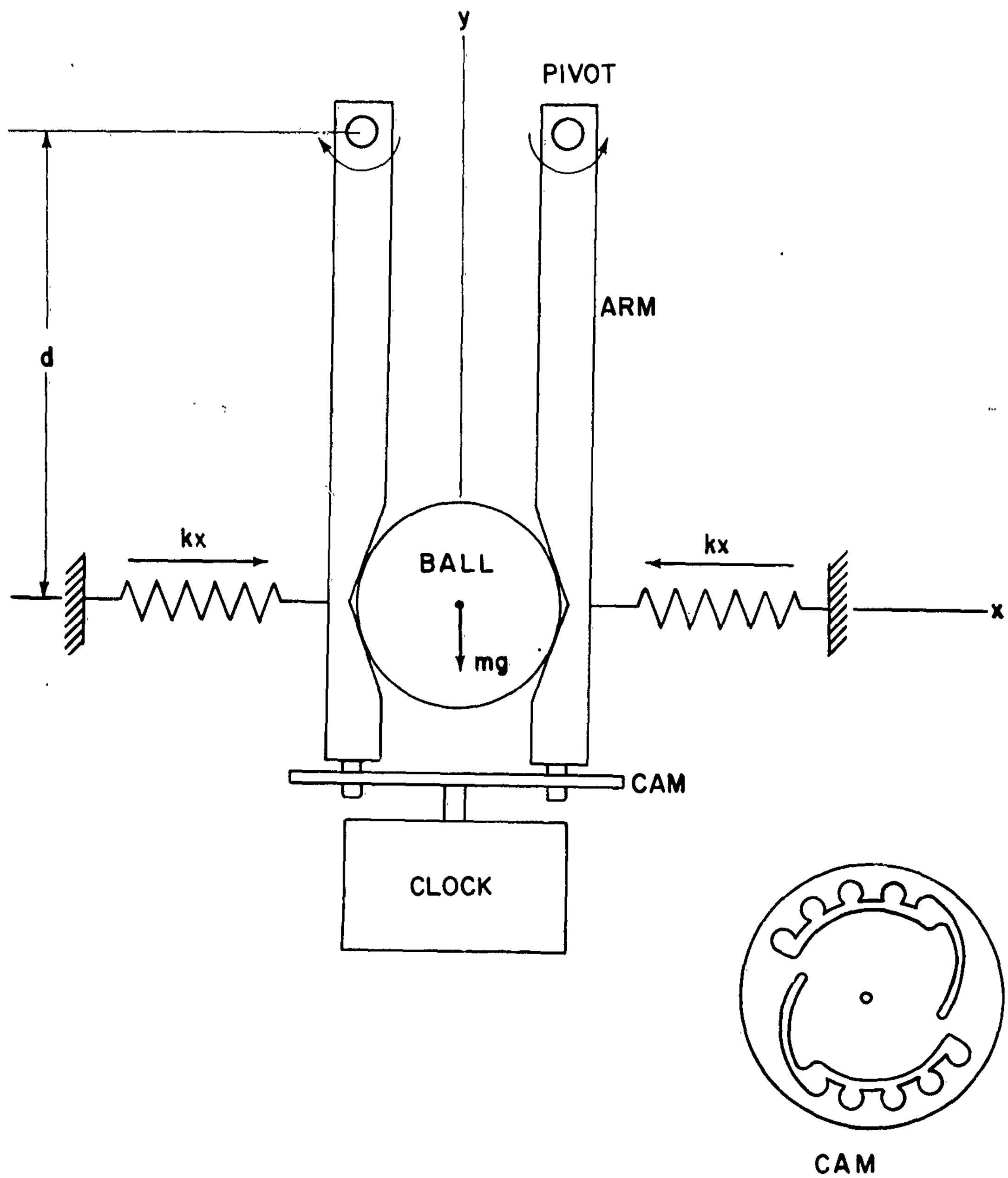
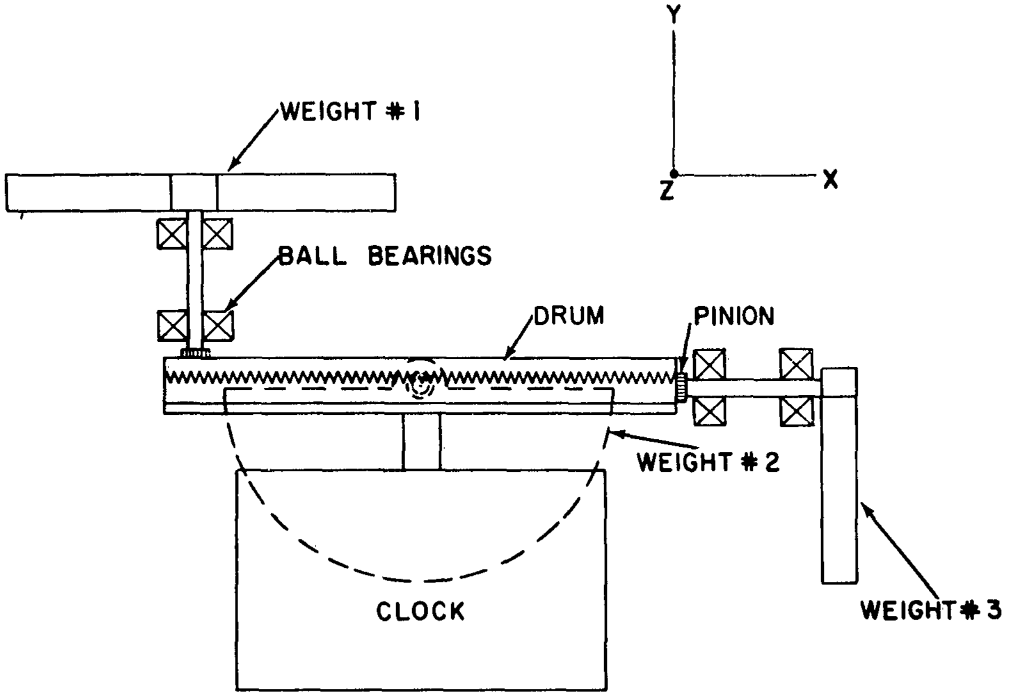
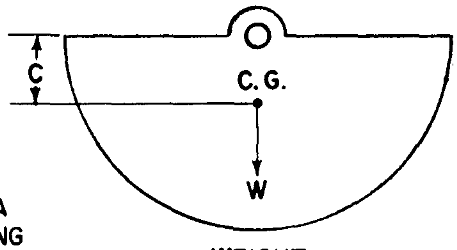


FIG. 1 BALL TORQUE VS PIVOTED ARM TORQUE

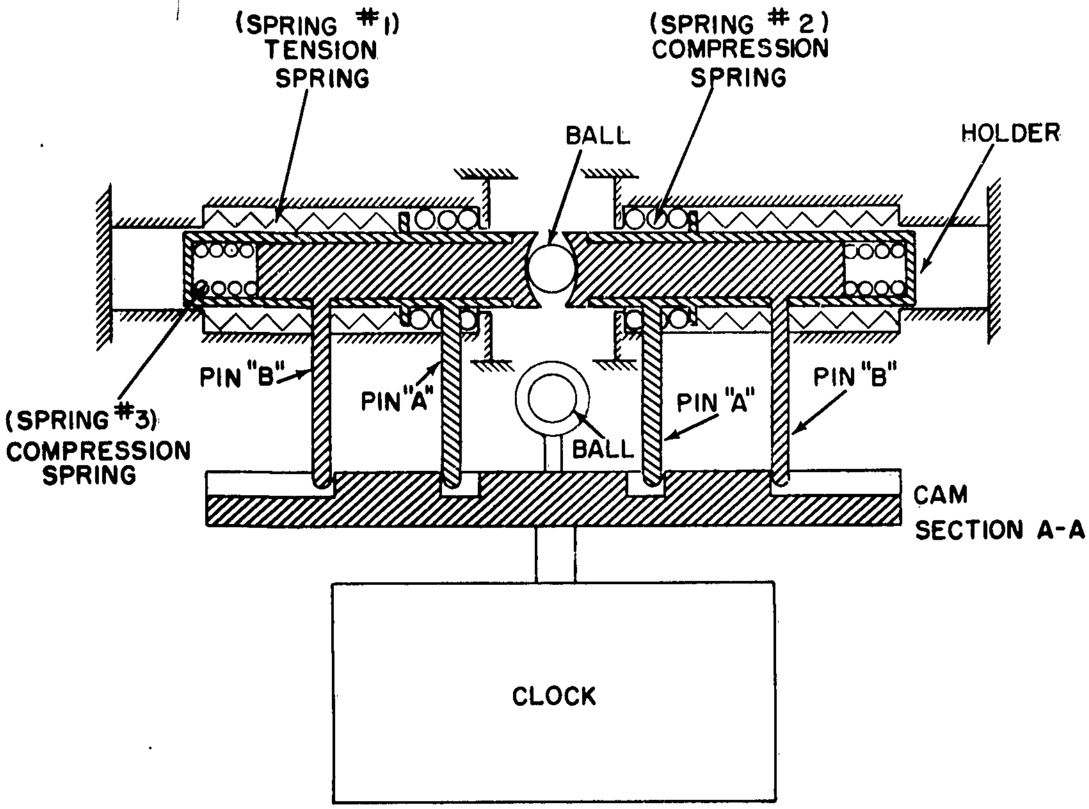




NOTES:

1. WITH G ACTING ALONG Y AXIS AS SHOWN, WEIGHT #1 OFFERS NO RESISTANCE DURING 360° ROTATION ON ITS AXIS.
2. AS SHOWN ABOVE, WEIGHTS 2 AND 3 ARE AT A POINT OF ZERO TORQUE; HOWEVER BY ROTATING EACH 90°, THE TORQUE BECOMES A MAXIMUM OF Wc ON EACH.
3. CONDITION FOR MINIMUM SYSTEM TORQUE (2 Wc): G VECTOR PARALLEL TO PRINCIPAL AXIS.
4. CONDITION FOR MAXIMUM SYSTEM TORQUE (2.414 Wc): G VECTOR MAKES 45° ANGLE WITH 2 AXES, NORMAL TO OTHER AXIS.

FIG. 2 ROTATING UNBALANCED WEIGHTS



NOTES:

1. WHEN PIN "A" REACHES A SLOT DURING THE CAM ROTATION, THE ENTIRE HOLDER MOVES OUT AND BACK UNDER THE ACTION OF SPRINGS 1 AND 2. IT IS THEN CAMMED FROM A TO B AS SHOWN IN THE SKETCH.
2. WHEN THE BALL HAS CLEARED THE HOLDERS, SPRING 3 ADVANCES PIN B ON PIN A, LOCKING THE CLOCK.

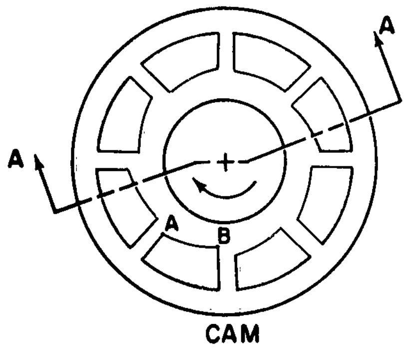


FIG. 3 POSITION OF BALL IN FREE FALL

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